

CDF Multi-Muon Events and Singlet Extensions of the MSSM

Florian Domingo, Ulrich Ellwanger

*Laboratoire de Physique Théorique, CNRS – UMR 8627,
Université de Paris-Sud, F-91405 Orsay, France*

Abstract

We discuss a generalization of the minimal supersymmetric extension of the Standard Model in the form of three additional singlet superfields, which would explain the essential features of the CDF multi-muon events presented recently: a large production cross section of ~ 100 pb originates from the production of a CP-odd scalar A with a mass in the 70 – 80 GeV range and a large value of $\tan \beta \sim 40$. The CP-odd scalar A decays dominantly into CP-odd and CP-even scalars a_1 and h_1 , which generate decay cascades $h_1 \rightarrow 2h_2 \rightarrow 4a_2 \rightarrow 8\tau$, and $a_1 \rightarrow h_1a_2$ with h_1 decaying as above. The decay $a_2 \rightarrow \tau^+\tau^-$ is slow, leading to a lifetime of $\mathcal{O}(20)$ ps. The phenomenology of the model differs from similar scenarios presented before in that one of the two cascades leads to 10 instead of 8 τ -leptons, and additional production processes like associate A production with $b\bar{b}$ pairs are relevant.

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1 Introduction

In a recent CDF publication [1] a sample of unusual multi-muon events was studied, which are characterized by the following properties: i) a large rate of additional muons inside a cone of 36.8° ($\cos\theta \geq 0.8$) around the direction of the trigger muon; ii) large impact parameters (displaced vertices), and iii) an unusually large cross section of the order of 75 pb.¹ Since neither Standard Model processes nor known detector effects can explain the nature of these events at present, they were referred to as ghost events.

In [2], some members of the CDF collaboration investigated to which extent the properties of the ghost events can be understood in the context of a phenomenological scenario based on cascade decays of new particles. First, the sign-coded multiplicity distribution of additional muons inside the $\cos\theta \geq 0.8$ cone coincides with the assumption that originally $4\tau^+ + 4\tau^-$ leptons were produced. As a hypothetical origin for the 8 τ -leptons, the authors of [2] considered the pair production of new particles h_1 via $p\bar{p} \rightarrow H \rightarrow h_1 h_1$, without specifying the nature of H (which could be a known or a new gauge boson, or another new particle). Subsequently, each of the h_1 particles is assumed to produce the decay cascade $h_1 \rightarrow 2h_2 \rightarrow 4h_3 \rightarrow 4(\tau^+ + \tau^-)$, generating two multi-muon cones per event. h_2 and h_3 denote additional new states, with h_3 decaying as $h_3 \rightarrow \tau^+ + \tau^-$.

In order to explain the high multiplicity of additional muons *inside* the $\cos\theta \geq 0.8$ cones, the particle h_1 must be relatively light. The best fit [2] to the invariant mass distributions inside the $\cos\theta \geq 0.8$ cones in [1] is obtained for h_1 , h_2 and h_3 masses near the lower limits for which the cascade is kinematically allowed: $m_{h_3} \sim 3.6 \text{ GeV} \gtrsim 2m_\tau$, $m_{h_2} \sim 7.3 \text{ GeV} \gtrsim 2m_{h_3}$ and $m_{h_1} \sim 15 \text{ GeV} \gtrsim 2m_{h_2}$. In order to explain the large impact parameters, at least one of the h_1 , h_2 or h_3 particles must have a long lifetime. The best fit [2] to the impact parameter distributions in [1] corresponds to the assumption that h_3 has a long lifetime of ~ 20 ps. The origin of the large cross section (for the production of H in this scenario) was left unexplained in [2].

Some comments on the multi-muon study by the CDF collaboration [1] and the phenomenological interpretation in [2] were published in [3], wherein proposals for additional studies/plots were made, and some difficulties with the phenomenological scenario in [2] were pointed out, on which we will comment later. Furthermore, different phenomenological scenarios (various types of micro-cascades $h_i \rightarrow f\bar{f}'h_{i+1}$) were proposed in [3], which could provide a better fit to the data.

Theoretical models, in which multi-lepton events at hadron colliders can be expected, have already been considered before [4–8]. One class of such models contains a rich nearly hidden sector (a “hidden valley”), which interacts only weakly with the Standard Model (SM) particles, as via a heavy Z' gauge boson, or via a small kinetic mixing between the SM and the hidden sector gauge fields [4–8]. It seems possible to explain the recently observed high-energy components of cosmic rays as remnants of dark matter annihilation in such models [9]. (See [10] for a discussion of string vacua including D-branes, where a light hyperweak gauge boson can connect the SM with a hidden sector, and ghost-like events can occur.)

¹The precise value of the necessary total cross section depends on the fraction of the events which survive the cuts applied in [1], which requires a model specific simulation.

Multi-lepton events at hadron colliders are also possible within the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [11–17], where the Higgs sector of the MSSM is extended by a singlet superfield S . The extended Higgs sector can contain a light CP-odd state a_1 with a mass below the $b\bar{b}$ threshold of ~ 10.5 GeV, such that a_1 decays dominantly as $a_1 \rightarrow \tau^+\tau^-$. If, in addition, the SM-like Higgs scalar h_{SM} decays dominantly as $h_{SM} \rightarrow a_1 + a_1$, events with 4 τ -leptons could be the only signal of h_{SM} , rendering its discovery quite difficult (see [18–20] and refs. therein). Alternatively, two leptons can originate from a bino decay into a singlino-like Lightest Supersymmetric Particle (LSP) [21, 22]. However, in both cases the large number of muons observed by CDF is not achieved.

In the present paper we consider the extension of the Higgs sector of the MSSM by several (three) singlets in order to discuss whether the properties of the CDF ghost events could be understood in such a setup. An extended Higgs sector was already implicitly suggested by the authors of [2] as a source of the states h_1 , h_2 and h_3 , and the construction of corresponding models leading to the desired masses in the range 3.5 – 15 GeV does not seem very difficult at first sight. However, in practice various problems appear: First, the unusually large production cross section must be explained. Second, the desired decay channels must be dominant, and at least one large lifetime must occur. Third, and most importantly, present constraints from colliders (notably LEP), B physics etc. on such an extended Higgs sector must be satisfied. In the worst case it may be impossible to satisfy all these conditions simultaneously, at least once the masses and couplings of the extended Higgs sector are constrained by supersymmetry.

Hence, it is important to look for a “go-theorem”: a concrete model, which has all these desired properties. Here we present such a model, which has the following structure: The starting point is the NMSSM involving a singlet superfield S , whose vacuum expectation value (vev) solves the μ -problem of the MSSM. We consider a region in the parameter space of the NMSSM, where the lightest CP-odd Higgs state in the H_u - H_d - S sector (denoted by A subsequently) has a mass in the 70 – 80 GeV range and has both large singlet and large doublet components of $\sim 85\%$ and $\sim 50\%$ respectively. Assuming a large value of $\tan\beta \sim 40$, the production cross section of A via gluon-gluon fusion at the Tevatron can be ~ 100 pb [23]. In the corresponding region in parameter space, the CP-even Higgs states in the H_u - H_d - S sector as well as the second CP-odd state have masses above 114 GeV, in which case all LEP constraints on various Higgs production processes [24] are satisfied. (The precise Higgs masses as well as various B-physics observables depend on the soft supersymmetry breaking gaugino, squark and slepton masses and couplings, for which ranges of desired values can be found without particular effort.)

To the Higgs sector of the NMSSM we add two more singlets S_1 and S_2 , which contain two more CP-even states $h_{1,2}$ and two more CP-odd states $a_{1,2}$. (From here onwards, the indices 1,2 denote the additional singlets of the model rather than the states introduced in [2].) These supplementary fields allow for many additional Yukawa couplings and soft terms, but for simplicity we assume that most of the possible Yukawa couplings vanish or are negligibly small (considering small Yukawa couplings, as those appearing in the SM, as natural). Then, the following situation can be achieved without fine tuning, assuming corresponding values of the additional soft terms: The mass matrices of the $h_{1,2}$ and $a_{1,2}$ states are nearly diagonal, with eigenvalues in the 3.5 – 20 GeV range. A Yukawa coupling

between S and S_1 remains relatively large, and as a consequence the CP-odd state A of the H_u - H_d - S sector decays dominantly into $h_1 + a_1$ (as compared to $A \rightarrow b\bar{b}$). Subsequently, due to a small S_1 - S_2 mixing, h_1 decays as $h_1 \rightarrow 2h_2 \rightarrow 4a_2 \rightarrow 8\tau$, and a_1 as $a_1 \rightarrow h_1a_2$ with h_1 -decays as above.

The decay $a_2 \rightarrow \tau^+\tau^-$ is possible due to a tiny $S_2 - H_d$ mixing of $\mathcal{O}(10^{-5})$, implying a a_2 lifetime of $\mathcal{O}(20)$ ps. Assuming $m_{a_1} \sim 20$ GeV and $m_{h_1} \sim 15$ GeV, the first $A \rightarrow h_1a_1$ decay will generate two separate cones containing 8 or 10 τ -leptons (which are thus not completely symmetric) as well as displaced vertices. Thus, the essential properties of the phenomenological scenario of [2] are reproduced, and the required cross section is obtained.

On the other hand the concrete model makes it clear that a phenomenological analysis based on a single process can be incomplete or even misleading: In the present scenario, the CP-odd state A will also be produced in association with $b\bar{b}$ pairs with a cross section of $\sim 30\%$ of the production via gluon-gluon fusion [23]. In $\sim 25\%$ of these cases, a b or \bar{b} decay will generate at least one additional muon, which can end up in one of the cones defined by the trigger muons. These additional muons will have an impact on observables like $\sum |p_T|$ and invariant masses, whose precise effect can only be studied with the help of simulations, which are beyond the scope of the present paper. (Likewise, the production and the decays of the heavier states of the H_u - H_d - S sector can contribute to the observables.) As already underlined in [3], an analysis of the data involving more stringent cuts than the ones presented in [1] (as muon charge selection rules) should make it easier to constrain – or to verify – concrete models as the one discussed here.

We are aware of the fact that the properties of the CDF multi-muon event samples still need to be confirmed, notably by the D0 collaboration. Nevertheless we found it useful to develop a concrete model, which indicates which additional complications can be expected and which, in any case, extends the perimeter of possible signals that may be expected at hadron colliders. Of course, if the properties of the multi-muon event samples are confirmed, it is also interesting to know that relatively simple singlet extensions of the MSSM can generate such signals. In the next section we will present the Lagrangian and discuss the parameters of the model. Its phenomenology and conclusions will be presented in section 3.

2 A toy model

As mentioned in the introduction, we consider a supersymmetric extension of the SM involving an extended Higgs sector, which consists of the MSSM doublets H_u , H_d and three singlet superfields S , S_1 and S_2 . A priori, a large number of terms could appear in the superpotential W , even after the restriction to scale invariant Yukawa couplings as motivated by a solution of the μ -problem of the MSSM. On the other hand, small or vanishing Yukawa couplings are “technically natural” (stable under quantum corrections) in supersymmetry, and we use this freedom to omit most of the allowed couplings.

The relevant Higgs dependent terms in the superpotential W are assumed to be given by

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + \lambda_1 S S_1^2 + \frac{\kappa_1}{3} S_1^3 + \lambda_2 S_1 S_2^2 + \frac{\kappa_2}{3} S_2^3. \quad (2.1)$$

The first two terms correspond to the ones of the NMSSM [11–17], where the vev $s \equiv \langle S \rangle$ generates an effective μ -parameter $\mu_{\text{eff}} = \lambda s$. The terms proportional to κ_1 and κ_2 serve to stabilize the scalar potential for the vevs $s_1 \equiv \langle S_1 \rangle$ and $s_2 \equiv \langle S_2 \rangle$, and λ_1 and λ_2 induce couplings between S and S_1 , and between S_1 and S_2 , respectively.

The soft terms in the Higgs sector are the scalar masses squared and trilinear couplings

$$m_{H_u}^2, m_{H_d}^2, m_S^2, m_{S_1}^2, m_{S_2}^2, A_\lambda, A_\kappa, A_{\lambda_1}, A_{\kappa_1}, A_{\lambda_2} \text{ and } A_{\kappa_2}. \quad (2.2)$$

It is straightforward to work out the tree level Higgs mass matrices and couplings from the superpotential and the soft terms, which leads to quite lengthy and not very transparent expressions. Instead of presenting them, we first consider the “decoupling limit” $\lambda_2 \rightarrow 0$. As it becomes evident from the superpotential, all components of the superfield S_2 decouple from H_u , H_d , S and S_1 in this limit. Furthermore one finds that for a wide range of parameters (for $A_{\kappa_1}^2$ not too large and positive $m_{h_1}^2$, see eq. (2.3) below), the vev s_1 vanishes, since terms linear in s_1 in the scalar potential are proportional to λ_2 . Then the mass matrices in the Higgs sector are block-diagonal:

In the NMSSM sector H_u - H_d - S one re-obtains the well known 3×3 (2×2) mass matrices for the CP-even (CP-odd) states [11–17]. In addition, the mass matrices for the CP-even $h_{1,2}$ and CP-odd $a_{1,2}$ states are diagonal. In the case of the vev s_2 , we assume that $|A_{\kappa_2}|$ is sufficiently large such that the vev s_2 is nonvanishing (which avoids degenerate h_2 , a_2 states and a massless neutralino ψ_2). Then it is convenient to express $m_{S_2}^2$ in terms of s_2 , κ_2 and A_{κ_2} through the minimization equation of the scalar potential, after which the masses of the physical states $h_{1,2}$ and $a_{1,2}$ can be written as

$$\begin{aligned} m_{h_1}^2 &= m_{S_1}^2 + 2\lambda_1 A_{\lambda_1} s + 2\kappa\lambda_1 s^2 - 2\lambda\lambda_1 v_u v_d + 4\lambda_1^2 s^2, \\ m_{a_1}^2 &= m_{S_1}^2 - 2\lambda_1 A_{\lambda_1} s - 2\kappa\lambda_1 s^2 + 2\lambda\lambda_1 v_u v_d + 4\lambda_1^2 s^2, \\ m_{h_2}^2 &= \kappa_2 s_2 (A_{\kappa_2} + 4\kappa_2 s_2), \\ m_{a_2}^2 &= -3\kappa_2 A_{\kappa_2} s_2 \end{aligned} \quad (2.3)$$

where v_u , v_d denote the vevs of the neutral components of H_u , H_d .

Evidently there exist sufficient free parameters $m_{S_1}^2$, λ_1 , A_{λ_1} , s_2 , κ_2 and A_{κ_2} in the S_1 - S_2 sector in order to generate a spectrum like

$$m_{a_1} \sim 20 \text{ GeV}, m_{h_1} \sim 16 \text{ GeV}, m_{h_2} \sim 8 \text{ GeV}, m_{a_2} \sim 4 \text{ GeV}, \quad (2.4)$$

which render the cascade decays described in the introduction kinematically possible, with relatively light initial states h_1 and a_1 . (The masses of the additional neutralinos are given by $m_{\psi_1} = 2\lambda_1 s$ and $m_{\psi_2} = 2\kappa_2 s_2$. ψ_1 is too heavy to be produced in A decays, and the $\text{BR}(A \rightarrow \psi_2 \bar{\psi}_2)$ vanishes in the decoupling limit.)

Of course, the desired cascade decays of h_1 and a_1 require the presence of couplings $g_{h_1 h_2 h_2}$, $g_{a_1 h_1 a_2}$ and $g_{a_2 \tau^+ \tau^-}$, which are absent in the decoupling limit $\lambda_2 \rightarrow 0$. (The coupling $g_{h_2 a_2 a_2}$ is of the order $\kappa_2 A_{\kappa_2}$ and not suppressed in the decoupling limit.) One can check that a small value of λ_2 will generate couplings of the order (modulo Yukawa couplings and a dimensionful parameter like an A -term or a vev) $g_{h_1 h_2 h_2} \sim g_{a_1 h_1 a_2} \sim \lambda_2$, $g_{a_2 \tau^+ \tau^-} \sim \lambda_2^2$. One finds that for $\lambda_2^2 \sim 10^{-5}$, the a_2 lifetime will be of the order 20 ps as desired, but which has no noticeable effect on the eigenvalues of the mass matrices above.

In the NMSSM sector, the tree level mass matrices receive considerable radiative corrections depending on the squark, slepton and gaugino masses and trilinear couplings. These are included in the code NMHDECAY/NMSSMTools [25–27], which computes the NMSSM Higgs masses and couplings as functions of the parameters in the Lagrangian. As independent parameters in the Higgs sector of the NMSSM, one can choose [25–27]

$$\lambda, \kappa, A_\kappa, \tan\beta, \mu_{\text{eff}} \equiv \lambda s, M_A^2 \equiv \frac{2\mu_{\text{eff}}(A_\lambda + \kappa s)}{\sin 2\beta}. \quad (2.5)$$

Large cross sections of Higgs particles at hadron colliders occur at large values of $\tan\beta$, for which the coupling of H_d to down quarks is proportional to $\tan\beta$. Then, the b quark loop induced gluon-gluon fusion process has a cross section amplified by $\sim \tan^2\beta$ with respect to the corresponding cross section for the production of a SM Higgs scalar. On the other hand, the cross section via gluon-gluon fusion decreases strongly with increasing Higgs masses, but low CP-even Higgs masses are strongly constrained by LEP [24]. Therefore we concentrate on a region in the NMSSM parameter space (2.5) at large $\tan\beta$ where a CP-odd Higgs scalar A has a mass m_A below 100 GeV, but large enough to render the decay $A \rightarrow h_1 a_1$ (with A on-shell) possible. Also, the decay $A \rightarrow h_1 a_1$ should have a larger branching ratio than the decay $A \rightarrow b\bar{b}$, which requires a considerable singlet S component of A without a too large suppression of the coupling of A to b quarks (see the next section).

Finally, LEP constraints on all CP-even Higgs scalars as well as constraints from B physics (the branching ratios $\text{BR}(B \rightarrow X_s \gamma)$, $\text{BR}(\bar{B}^+ \rightarrow \tau^+ \nu_\tau)$, $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ and the mass differences ΔM_q , $q = d, s$), which are particularly relevant at large $\tan\beta$, should be satisfied. All these constraints are checked in the code NMHDECAY/NMSSMTools [25–27], which we used in the search for acceptable regions in the parameter space (2.5) of the model. Clearly, Higgs masses as well as B physics observables depend also on the soft supersymmetry breaking gaugino, squark and slepton masses and couplings, which have to be specified.

In fact, for large $\tan\beta \sim 40$ and non-negligible NMSSM Yukawa couplings λ and κ a phenomenologically acceptable region in the parameter space exists, in which A has a mass in the 70 – 80 GeV range and H_d - and S -components of $\sim 50\%$ and $\sim 85\%$, respectively. An example is given by the following point in parameter space, where

$$\lambda = .28, \kappa = .33, A_\kappa = -36.5, \tan\beta = 40, \mu_{\text{eff}} = 240 \text{ GeV}, M_A = 420 \text{ GeV}. \quad (2.6)$$

The gaugino masses are $M_1 = 150 \text{ GeV}$, $M_2 = 300 \text{ GeV}$, $M_3 = 1 \text{ TeV}$, the left-handed and right-handed up-type squark masses are 1.5 TeV, the right-handed down-type squark masses are given by 1 TeV, the slepton masses by 500 GeV, $A_{\text{top}} = A_{\text{bottom}} = 1.8 \text{ TeV}$ and $A_\tau = 300 \text{ GeV}$.

For these parameters, the lightest CP-odd Higgs mass m_A and its decomposition $A = N_{A,A_u} A_u + N_{A,A_d} A_d + N_{A,S} A_s$ (where A_u , A_d and A_s are the neutral CP-odd components of H_u , H_d and S) are given by

$$m_A = 70 \text{ GeV}, N_{A,A_u} = 0.01, N_{A,A_d} = 0.56, N_{A,S} = 0.83. \quad (2.7)$$

The masses of the three CP-even Higgs scalars are 114.5 GeV, 270 GeV and 561 GeV, and the masses of the second CP-odd and charged Higgs scalars are 300 GeV and 264 GeV, respectively. Further properties of this point in parameter space, which are relevant for the CDF ghost events, will be discussed in the next section.

3 Phenomenology of the toy model

In order to estimate the production cross section of A via gluon-gluon fusion at the Tevatron, one has to determine its reduced coupling X_d to down-type quarks (normalized to the SM Higgs coupling),

$$X_d = \tan \beta \times N_{A,A_d} \quad (= 22.2), \quad (3.1)$$

where the value in parenthesis is the one for the point given in (2.6), (2.7). Then, the corresponding production cross sections for the Tevatron in [23] can be rescaled appropriately, and extrapolated to $m_A = 70 - 80$ GeV. For $m_A = 70$ GeV and $X_d \sim 22$ one obtains $\sigma(p\bar{p} \rightarrow A + X) \sim 100$ pb, even somewhat larger than required.

Subsequently, we have to estimate the A decay branching fractions. In the absence of the $S_{1,2}$ sector, A would decay to $\sim 90\%$ into $b\bar{b}$ with a partial width

$$\Gamma_{b\bar{b}} = \frac{3 G_F}{4 \sqrt{2} \pi} X_d^2 m_b^2 m_A \sqrt{1 - \frac{4 m_b^2}{m_A^2}}, \quad (3.2)$$

which gets enhanced by $\sim 20\%$ by QCD corrections. In the presence of a coupling $g_{Ah_1a_1}$, the partial width for the decay $A \rightarrow h_1a_1$ is

$$\Gamma_{h_1a_1} = \frac{g_{Ah_1a_1}^2}{16 \pi m_A} \sqrt{\left(1 - \frac{m_{h_1}^2}{m_A^2} - \frac{m_{a_1}^2}{m_A^2}\right)^2 - 4 \frac{m_{h_1}^2 m_{a_1}^2}{m_A^4}}. \quad (3.3)$$

Numerically, one obtains for the ratio

$$R = \frac{\Gamma_{h_1a_1}}{\Gamma_{b\bar{b}}} \sim \left(\frac{36 g_{Ah_1a_1}}{X_d m_A}\right)^2. \quad (3.4)$$

In order to obtain a branching fraction for $A \rightarrow h_1a_1$ larger than $\sim 80\%$, such that the production cross section $\sigma(p\bar{p} \rightarrow A \rightarrow h_1a_1)$ is larger than ~ 80 pb, we should have $R \gtrsim 4$.² For the values of X_d and m_A above, this can be obtained for $g_{Ah_1a_1} \gtrsim 86$ GeV. In the present model, $g_{Ah_1a_1}$ is given by

$$g_{Ah_1a_1} = \frac{N_{A,S}}{\sqrt{2}} \lambda_1 (A_{\lambda_1} + 2\kappa s) \quad (3.5)$$

with $N_{A,S}$ as in (2.7). Note that $g_{Ah_1a_1}$ is not suppressed in the decoupling limit $\lambda_2 \rightarrow 0$. It is easy to find values for $\lambda_1 \sim 0.52$ and $A_{\lambda_1} \sim -283$ GeV such that $g_{Ah_1a_1}$ is sufficiently large, and the masses m_{h_1} and m_{a_1} obtained from (2.3) have the desired values.

After the dominant decay $A \rightarrow h_1a_1$, h_1 and a_1 cannot decay at tree level in the decoupling limit $\{\lambda_2, s_1\} \rightarrow 0$, where h_1 and a_1 do not mix with the H_u - H_d - S sector. Small values of λ_2 (and appropriate natural values for A_{λ_2} , κ_2 and A_{κ_2}) are sufficient in order to generate the dominant decays $h_1 \rightarrow h_2h_2$, $h_2 \rightarrow a_2a_2$ and $a_1 \rightarrow h_1a_2$, which we assume to be kinematically allowed, and which produce the cascades described in the introduction. The

²We recall the footnote on page 1, according to which the necessary total cross section can be somewhat larger or smaller.

decay of a_2 into quarks and leptons is made possible only through its small mixing $\sim \lambda_2^2$ with the H_u - H_d - S sector. For large $\tan\beta$, a_2 mixes dominantly with H_d , from which it inherits the couplings proportional to the down-type fermion masses leading to the dominant decay $a_2 \rightarrow \tau^+\tau^-$ (for $2m_b > m_{a_2} \gtrsim 2m_\tau$). Herewith we have reproduced the essential features of the scenario proposed in [2], albeit with one of the two cascades (the one originating from a_1) leading to 10 rather than 8 τ -leptons in the final state, which will evidently imply some modifications of the plots presented in [2].

Next we comment on an issue raised in [3], where it has been noted that a Higgs-like coupling to τ -leptons implies a coupling to muons with a ratio m_μ/m_τ , and hence a ratio of branching ratios $\text{BR}(a_2 \rightarrow \mu^+\mu^-)/\text{BR}(a_2 \rightarrow \tau^+\tau^-) \gtrsim m_\mu^2/m_\tau^2 \sim 0.0035$. For m_{a_2} near $2m_\tau$ the ratio of branching ratios increases due to the kinematic suppression of the $\text{BR}(a_2 \rightarrow \tau^+\tau^-)$. In plots of the invariant mass of muons of opposite charges inside a cone, this could (should) generate a visible peak at m_{a_2} . This reasoning remains valid in our case, but we note that the kinematic suppression of the $\text{BR}(a_2 \rightarrow \tau^+\tau^-)$ near the threshold $m_{a_2} \rightarrow 2m_\tau$ is less important for CP-odd scalars (like a_2) as compared to CP-even scalars; accordingly, the ratio of branching ratios above will increase less dramatically near the threshold $m_{a_2} \rightarrow 2m_\tau$, which makes it somewhat more difficult to rule out the scenario through a non-observation of a peak in the $\mu^+\mu^-$ invariant mass distribution.

Finally we turn to the invariant mass distribution M of all muons – or of all tracks – for events in which both cones contain at least two muons (Fig. 35 in [1]). According to the simulations of the process $p\bar{p} \rightarrow H \rightarrow h_1h_1$ performed in [2] (in the notation of [2]), a resonance-like structure should be visible with a peak position depending on m_H (see Fig. 6 in [2]); however, the data do not show such a structure: the process simulated in [2] could not describe simultaneously the steep rise of the invariant mass distribution for small M , and the tail of the invariant mass distribution at large M , for any value of m_H .

In the present scenario we have to replace H by A with a mass in the 70 – 80 GeV range, which seems to describe only the invariant mass distribution for small M . Furthermore, one of the cones would contain 10 τ -leptons; however, this is possibly not yet enough in order to explain the tail of the invariant mass distribution at large M .

On the other hand, as already mentioned in the introduction, there exist additional production processes which have necessarily to be taken into account: the cross section for associate $b\bar{b} + A$ production can be estimated to be $\sim 30\%$ of the A production via gluon-gluon fusion (hence ~ 30 pb) for A masses in the range considered here [23]. In $\sim 25\%$ of these cases, a b or \bar{b} decay will generate at least one additional muon which can contribute to the tail of the invariant mass distribution at large M .

Furthermore, one of the heavier CP-even scalars (the one with a mass of ~ 270 GeV for the point above) as well as the heavier CP-odd scalar A_{heavy} (with a mass ~ 300 GeV here) have couplings to b quarks enhanced by factors of $\tan\beta = 40$ and $\tan\beta \times N_{A_{\text{heavy}}, A_d} \sim 33$, respectively. At least in regions in parameter space where their masses are still lower, these states – which will generate similar cascades leading to 8 – 10 τ -leptons – can also contribute to the tail of the invariant mass distribution at large M . Of course, further simulations are necessary in order to check these conjectures, but at first sight explanations of the invariant mass distributions for small and for large M seem possible. Clearly, these processes will also contribute to other observables like $\sum p_T$.

At last, a comment on the dark matter relic density in this model is appropriate. The LSP is the neutralino ψ_2 with a mass $m_{\psi_2} = 2\kappa_2 s_2 \approx m_{h_2} \gtrsim 2m_{a_2}$. Its annihilation is dominated by the processes $\psi_2 + \psi_2 \rightarrow h_2 \rightarrow a_2 + a_2$ and $\psi_2 + \psi_2 \rightarrow a_2 \rightarrow h_2 + a_2$. Subsequently the scalars a_2 (h_2) will decay into two (four) τ -leptons as at the end of the cascades relevant for the multi-muon events. The annihilation processes depend on the $\psi_2 \psi_2 h_2/a_2$ Yukawa coupling κ_2 , and on the trilinear coupling $g_{h_2 a_2 a_2}$ of the order of $\kappa_2 A_{\kappa_2}$. Whereas A_{κ_2} is determined by the desired values of m_{h_2} and m_{a_2} (2.3) to be $A_{\kappa_2} \sim -(1 - 1.5)$ GeV (and $\kappa_2 s_2 \sim 4$ GeV), the value of κ_2 is unconstrained so far. One can expect that, for a value of κ_2 in the range $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-1})$, the WMAP value $0.094 \lesssim \Omega_{\psi_2} h^2 \lesssim 0.136$ [28] for the dark matter relic density can be achieved.

To conclude, apart from the fact that the CDF multi-muon events [1] need to be confirmed notably by the D0 collaboration, additional studies of their properties would be desirable, as the ones pointed out in [3]: spatial correlations among displaced vertices, and invariant mass distributions of dimuon pairs depending on their relative charges. In any case, plots have to be compared with simulations of models.

We have presented a relatively simple model in the form of a multi-singlet extension of the MSSM, whose particle content and parameters have been chosen such that the essential features of the CDF multi-muon events can be reproduced, without contradicting constraints from other experiments. Already in this scenario, the phenomenology would be more complicated than the one discussed in [2]. Clearly, the particular values of the parameters of the model chosen in section 2 – and the corresponding masses and couplings – have been presented for illustrative purposes only, and eventually the complete phenomenologically acceptable region in parameter space could be studied. Together with further models, which will certainly be proposed soon, this will allow for comparisons or “best fits” to the data.

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